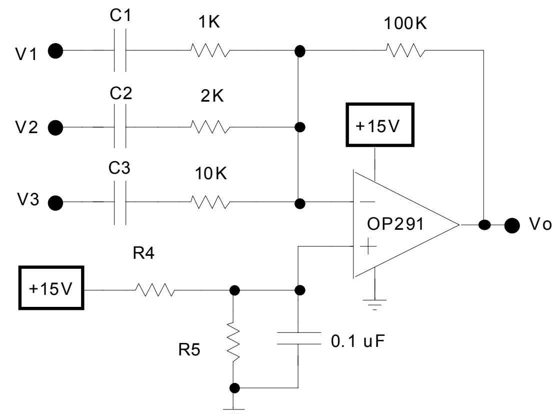
# EXERCISE - OP AMP FREQUENCY RESPONSE

No.1 Look up data sheets for specifications.

A) The op amp shown beside operates from a single supply voltage, therefore determine $R_4$ and $R_5$ required to bias $V_o$ to +7,5V DC.



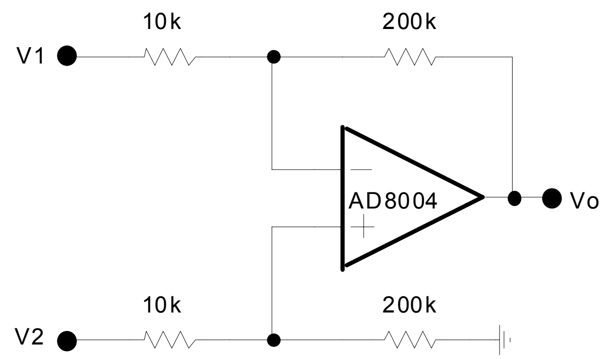

B) Assuming that $V_1$, $V_2$ and $V_3$ all range from 100 Hz to 10 kHz, calculate the standard values of $C_1$, $C_2$ and $C_3$ required to obtain the same low cutoff frequency and no attenuation of the input signals at all.

C) Sketch the three gain responses $V_o/V_1$, $V_o/V_2$ and $V_o/V_3$ on the same graph showing all relevant values.

D) Does the op amp have enough GBW for less than 1 dB attenuation of the HF signals? Explain.

No.2

Sketch the gain response of this circuit assuming typical parameters - fully label with all relevant parameters.

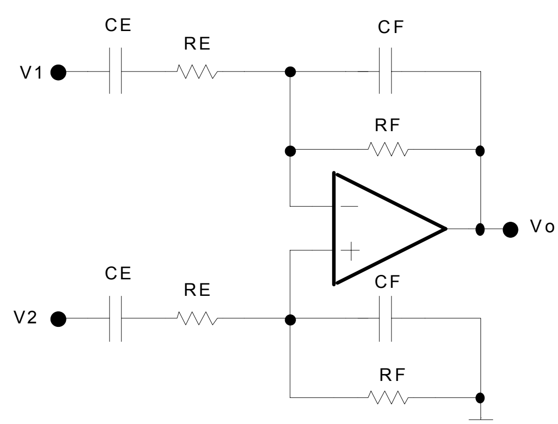



No.3

A) Prove that $A_{VF} = V_o/(V_2-V_1) = Z_F/Z_E$ assuming an ideal op amp.

B) Design the circuit for a gain of 26 dB and sufficient passband to accomodate the inputs whose frequency range is from 50 Hz to 50 kHz. Select the cutoff frequencies for 1 dB of attenuation at 50 Hz and 50 kHz.

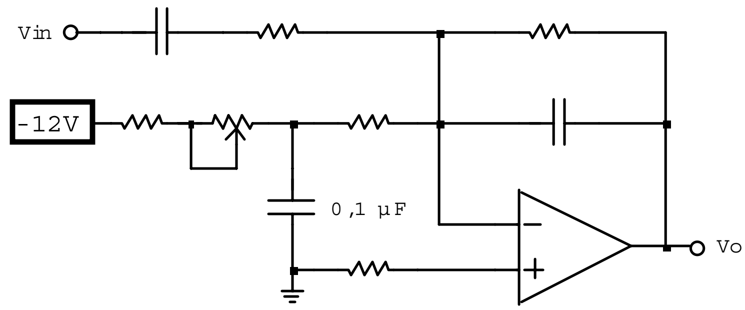
C) What is the minmum GBW required for the op amp for less than 10% deviation caused by the GBW on the high cutoff frequency?



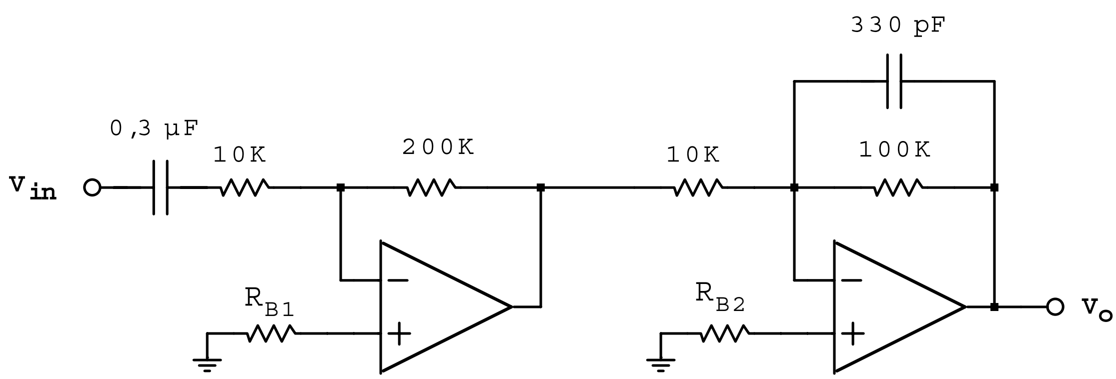
No.4

Design the circuit for a gain of 30 dB and for $V_o$(DC) trimmable for +5V±1V. Determine the capacitor values for a passband of 1 Hz to 1 kHz.

What is the minimum GBW required of the op amp for less than 1% deviation of the high cutoff frequency caused by GBW?




No.5




A) Determine the transfer function of each stage and sketch the gain response of each stage. Also sketch the overall gain response and label with all relevant parameters.

B) What GBW is sufficient for each stage for less than 10% error on $F_{Hi}$? Explain.

C) Determine the values of $R_{B1}$ and $R_{B2}$?

## SOLUTIONS

No.1 A) $R_4$ and $R_5$ are connected in series, therefore $I_4 = I_5$ and the resistor ratio is given by:

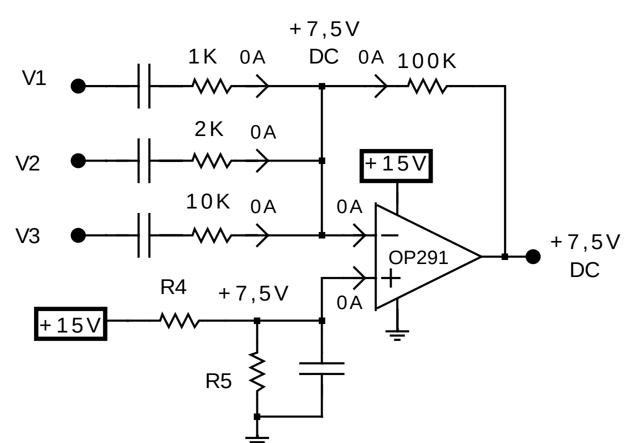
$$\frac{I_4\,R_4}{I_5\,R_5} = \frac{I_4\,R_4}{I_4\,R_5} = \frac{R_4}{R_5} = \frac{V_4}{V_5}$$

Now $V_4 = V_5 = 7.5V$, therefore $R_4 = R_5$

In addition, we should balance the op amp inputs for DC resistance:

$$R_4 \| R_5 = R_4 \| R_4 = 0{,}5\,R_4 = 100K$$

$$R_4 = R_5 = 200K$$



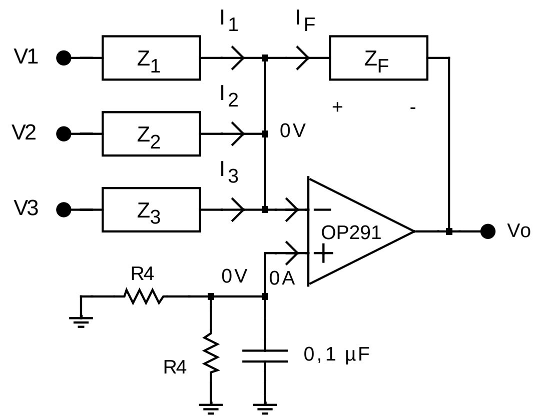
B)

$$V_o = -(I_1 + I_2 + I_3)Z_F$$

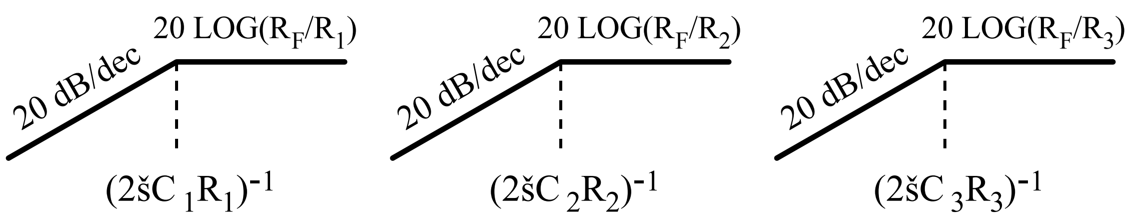
$$V_o = -\left(\frac{V_1}{Z_1} + \frac{V_2}{Z_2} + \frac{V_3}{Z_3}\right)Z_F$$

$$V_o = -\left(\frac{Z_F V_1}{Z_1} + \frac{Z_F V_2}{Z_2} + \frac{Z_F V_3}{Z_3}\right)$$

$$V_o = -\left(\frac{R_F V_1}{R_1 + \frac{1}{j\omega C_1}} + \frac{R_F V_2}{R_2 + \frac{1}{j\omega C_2}} + \frac{R_F V_3}{R_3 + \frac{1}{j\omega C_3}}\right)$$




$$V_o = -\left(\frac{R_F}{R_1} \times \frac{V_1}{1 + \frac{1}{j\omega\ R_1 C_1}} + \frac{R_F}{R_2} \times \frac{V_2}{1 + \frac{1}{j\omega\ R_2 C_2}} + \frac{R_F}{R_3} \times \frac{V_3}{1 + \frac{1}{j\omega\ R_3 C_3}}\right)$$




Make $F_{C1} = F_{C2} = F_{C3} = 0{,}1\ F_{min} = 10$ Hz so that the minimum frequency signals are not attenuated.

$C_1 = (2\pi F_C R_1)^{-1} = (2\pi \times 10 \times 1K)^{-1} = 15{,}9\ \mu F$, use **22 µF std**, $F_{C1} = 7{,}2$ Hz OK

$C_2 = (2\pi F_C R_2)^{-1} = (2\pi \times 7{,}2 \times 2K)^{-1} = 11\ \mu F$, use **10 µF std**, $F_{C2} = 7{,}96$ Hz OK

$C_3 = (2\pi F_C R_3)^{-1} = (2\pi \times 7{,}2 \times 10K)^{-1} = 2{,}21\ \mu F$, use **2,2 µF std**, $F_{C3} = 7{,}2$ Hz OK

C) The high cutoff frequency will be determined by the GBW of the op amp and $\beta_{V(HF)}$. Assume all $X_C$'s = 0 at HF.

$$R_{EQ} = 1K \| 2K \| 10K = 625$$

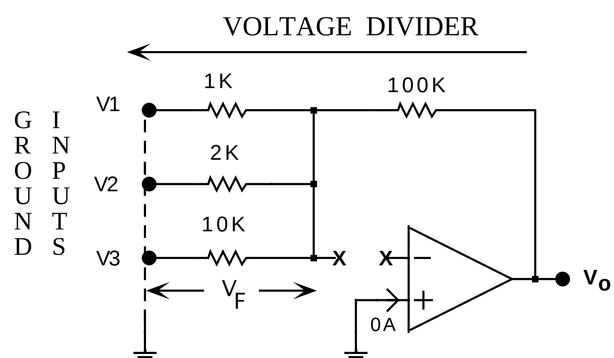
$$V_F = V_O \times \frac{R_{EQ}}{R_{EQ} + R_F} = V_O \times \frac{625}{625 + 100K}$$

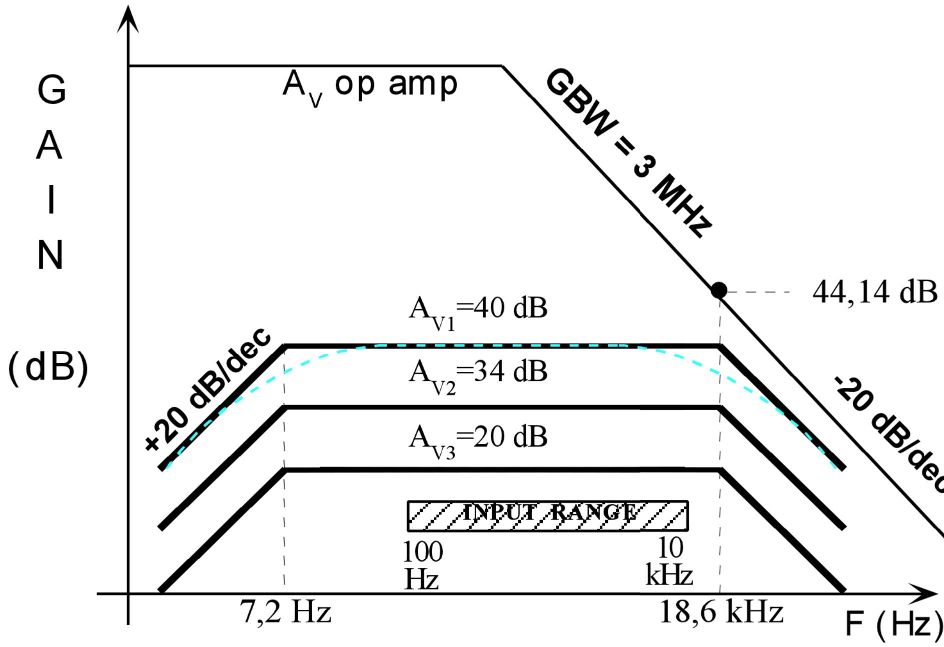
$$V_F = V_O \times \frac{1}{161} \Rightarrow \beta_V = \frac{V_F}{V_O} = \frac{1}{161} = 6{,}211m$$

$$BW = \beta_V \times GBW = \frac{3M}{161} = 18{,}63\ kHz$$

**How to find $\beta_{V(HF)}$**

All capacitors have close to zero reactance:






D) For 1 dB of attenuation at $F_{max}$, $F_{HI} = 2\ F_{max}$ or $GBW = 2\ F_{max}/\beta_V$ = 20k X 161 = 3,22 MHz. So the OP291 would be fine with its typical GBW of 3 MHz but not for units having a worst case minimum GBW. Therefore the OP291 is not adequate, one should pick an op amp with a worst case minimum GBW of 3,22 MHz.

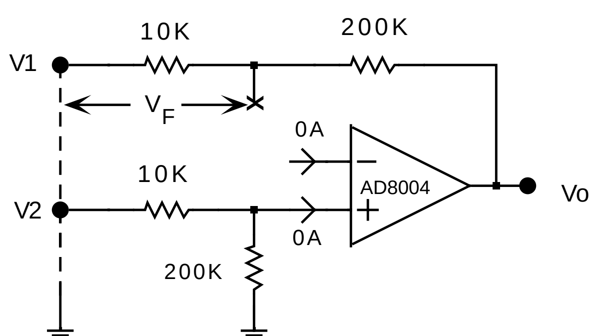
No.2

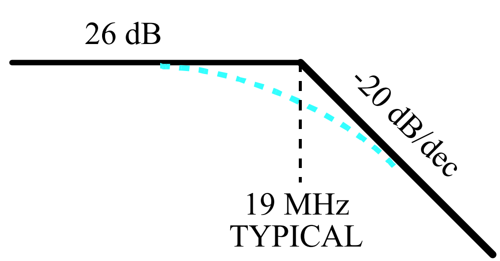
To find $\beta_V$, ground all inputs and open feedback loop, then find $V_F$ in terms of $V_o$.

$V_F = V_o$ X 10K /(10K + 200K) = $V_o/21$

$\beta_V = V_F/V_o = 1/21$

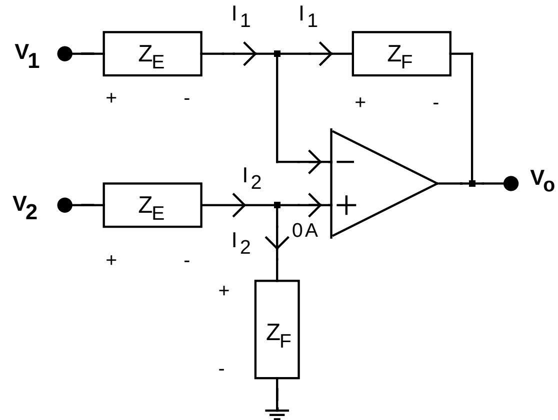
BW = $\beta_V$ X GBW = 400M/21 = 19,05 MHz typ




**Typical Gain Response**

No.3 A)




$$V^{+} = V^{-} = V_2 \times \frac{Z_F}{Z_E + Z_F}$$

$$V_o = V^{-} - I_1 Z_F = V^{-} - \left(\frac{V_1 - V^{-}}{Z_E}\right) Z_F$$

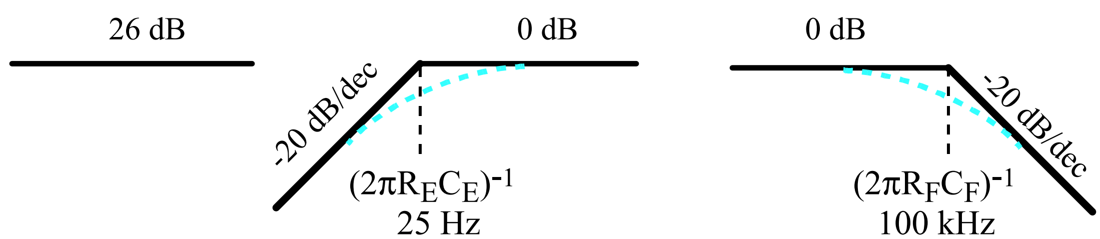
$$V_o = V^{-} + V^{-}\left(\frac{Z_F}{Z_E}\right) - V_1\left(\frac{Z_F}{Z_E}\right)$$

$$V_o = V^{-}\left(1 + \frac{Z_F}{Z_E}\right) - V_1\left(\frac{Z_F}{Z_E}\right)$$

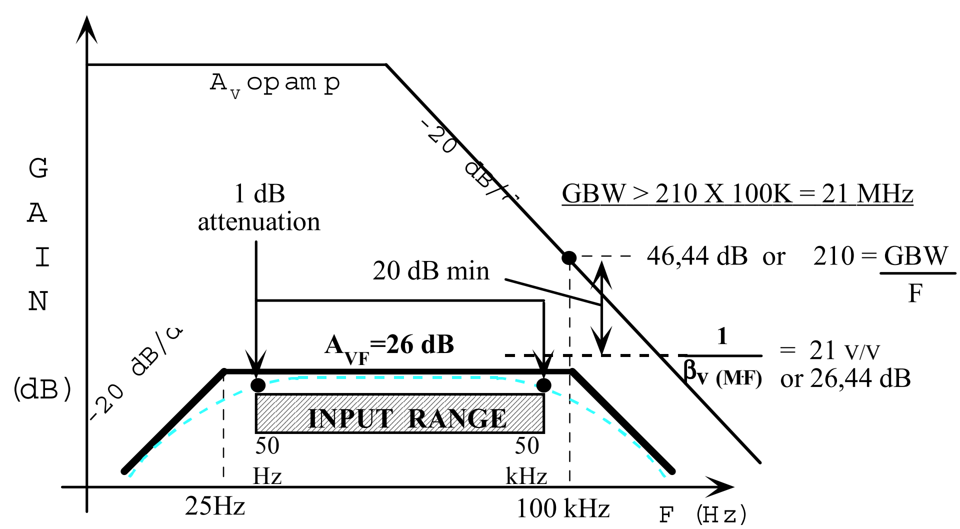
$$\boxed{V_o = V_2 \times \left(\frac{Z_F}{Z_E + Z_F}\right)\left(\frac{Z_E + Z_F}{Z_E}\right) - V_1\left(\frac{Z_F}{Z_E}\right) = V_2\left(\frac{Z_F}{Z_E}\right) - V_1\left(\frac{Z_F}{Z_E}\right) = \left(\frac{Z_F}{Z_E}\right) \times (V_2 - V_1)}$$

B) $$A_{VF} = \frac{Z_F}{Z_E} = \frac{R_F \| (1/SC_F)}{R_E + (1/SC_E)} = \frac{R_F}{R_E} \times \frac{1}{1 + \frac{1}{SC_E R_E}} \times \frac{1}{1 + SC_F R_F}$$

$$A_{VF} = \frac{R_F}{R_E} \times \frac{1}{1 + \frac{1}{SC_E R_E}} \times \frac{1}{1 + SC_F R_F}$$




For less than 10% error on $F_{HI}$ = 100 kHz, $A_V$ of op amp must be at least 20 dB above $(1/\beta_V)$ at F = $F_{HI}$. Tolerance of the components will introduce additional % error on $F_{LO}$ and $F_{HI}$.



$$Let \quad R_F = 20K,\ R_E = \frac{R_F}{|A_{VF}|} = \frac{20K}{20} = 1K$$

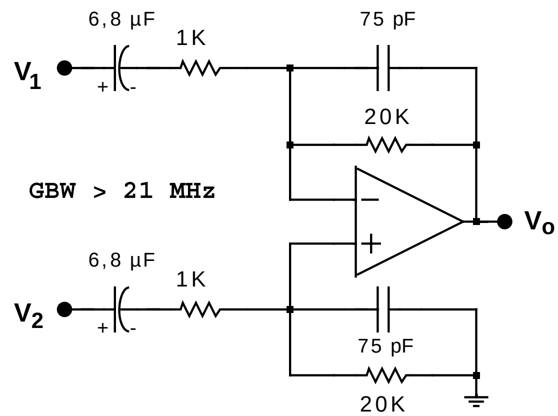
$$C_F = \frac{1}{2\pi R_F F_{Hi}} = \frac{1}{2\pi \times 20K \times 100K} = 79.6\ pF, \underline{use\ 75\ pF\ \ std} \quad \Rightarrow \quad F_{Hi} = \frac{1}{2\pi R_F C_F} = 106.1\ kHz$$

$$C_E = \frac{1}{2\pi R_E F_{Lo}} = \frac{1}{2\pi \times 1K \times 25} = 6.37\ \mu F, \underline{use\ 6.8\ \mu F\ \ std} \quad \Rightarrow \quad F_{Lo} = \frac{1}{2\pi R_E C_E} = 23.4\ Hz$$

**Final Circuit**

Stray capacitance will affect $F_{Hi}$ because $C_F$ = 75 pF is small and op amp GBW will lower $F_{Hi}$ by about 8,4% if GBW = 21 MHz, that is

$$F_{Hi} = 106{,}1k \times \left(\frac{100 - 8{,}4}{100}\right) = 97{,}2\ kHz$$




$$No.4 \qquad Let \quad R_E = 15K,\ R_F = |A_{VF}| \times R_E = 31.62 \times 15K = 474.3K, \underline{use\ 470K\ \ std}$$

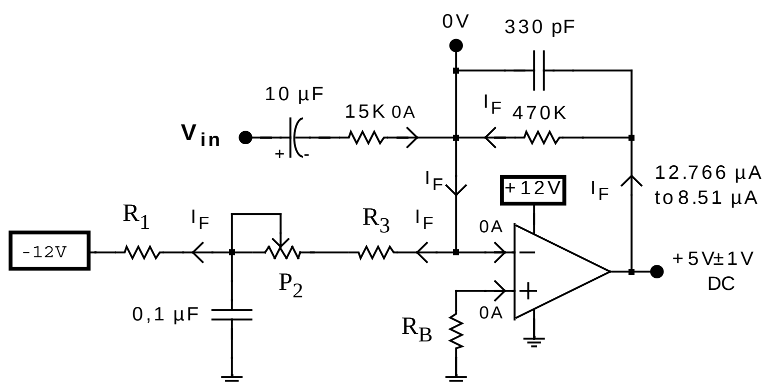
$$C_F = \frac{1}{2\pi R_F F_{Hi}} = \frac{1}{2\pi \times 470K \times 1K} = 338.6\ pF, \underline{use\ 330\ pF\ \ std} \quad \Rightarrow \quad F_{Hi} = \frac{1}{2\pi R_F C_F} = 1.026\ kHz$$

$$C_E = \frac{1}{2\pi R_E F_{Lo}} = \frac{1}{2\pi \times 15K \times 1} = 10.6\ \mu F, \underline{use\ 10\ \mu F\ \ std} \quad \Rightarrow \quad F_{Lo} = \frac{1}{2\pi R_E C_E} = 1.06\ Hz$$

$$R_B = 470K \| \left(470K + \frac{500K}{2} + 430K\right)$$

$$R_B = 333.6K \quad \underline{use\ 330K\ \ std}$$

**NOTE**: the 0,1 µF cap is used to filter +12V supply rail noise. $V_{in}$ must be positive all the time to ensure correct polarity of 10 µF polarised cap.
GBW > 100 $F_{Hi}$ ($1/\beta_V$) = 100 X 1K X 32.33 = 3,23 MHz for less than 1% error caused by GBW on $F_{Hi}$ = 1 kHz.




$$\beta_{V(MF)} = \frac{V^-}{V_o} = \frac{R_E}{R_E + R_F}$$

$$\frac{1}{\beta_{V(MF)}} = \frac{R_E + R_F}{R_E} = \frac{470K + 15K}{15K}$$

$$\frac{1}{\beta_{V(MF)}} = 32.33 \quad or \quad 30.19\ dB$$

$$R_{tot} = R_1 + P_2 + R_3 = 12V/12.766\,\mu A \rightarrow 8.51\,\mu A$$

$$R_{tot} = 0.94M\Omega \rightarrow 1.41M\Omega$$

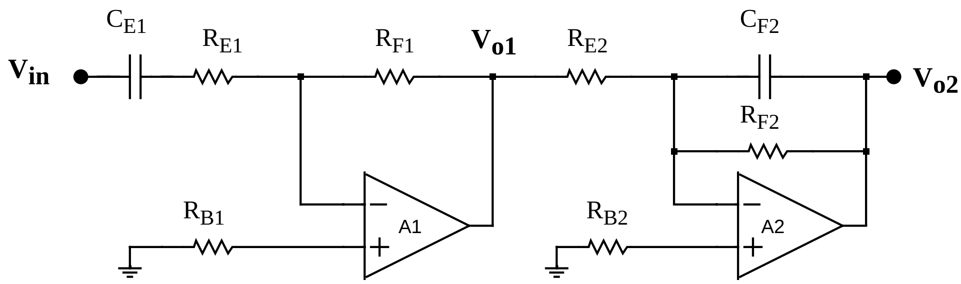
$$P_2 = \Delta R_{tot} = 0.94M - 1.41M = 470K \quad \underline{use\ 500K\ \ pot\ \ std}$$

$$R_1 + R_3 = R_{tot(\max)} - P_2 = 1.41M - 500K = 910K,$$

$$let \quad R_1 = 470K\ \ std,$$

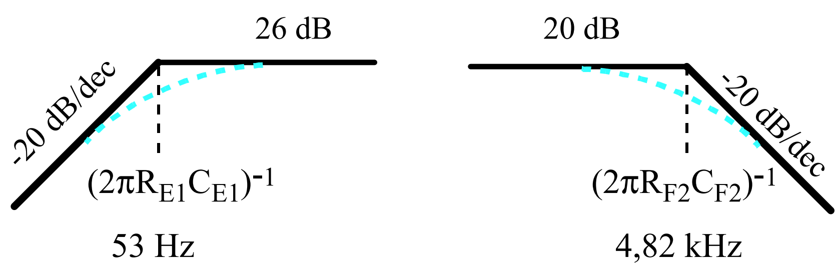
$$then \quad R_3 = 910K - 470K = 440K \quad \underline{use\ 430K\ \ std}$$

No.5 A)




$$A_{V\,(tot)} = A_{V1} \times A_{V2} = \left(-\frac{Z_{F1}}{Z_{F1}}\right) \times \left(-\frac{Z_{F2}}{Z_{F2}}\right) = \left(\frac{R_{F1}}{R_{E1} + \frac{1}{SC_{E1}}}\right) \times \left(\frac{R_{F2} \| \frac{1}{SC_{E2}}}{R_{E2}}\right)$$

$$A_{V\,(tot)} = \left(\frac{R_{F1}}{R_{E1}} \times \frac{1}{1 + \frac{1}{SR_{E1}C_{E1}}}\right) \times \left(\frac{R_{F2}}{R_{E2}} \times \frac{1}{1 + SC_{E2}R_{E2}}\right)$$

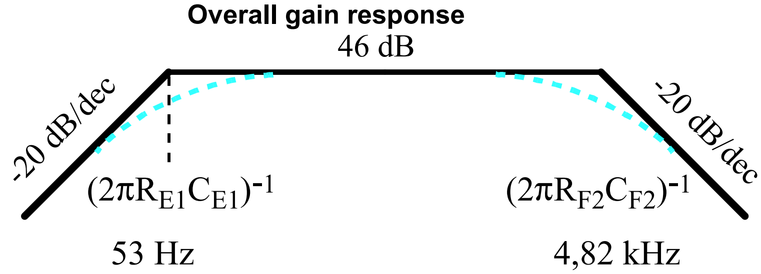



No.5 C)

$R_{B1} = 200k$

$R_{B2} = 10k \| 100k = 9,1k$

**Overall gain response**




No.5 B)

To minimise the impact of the high cutoff frequency of the first stage on the 4,82 KHz cutoff of the second stage, it should be at least one decade above 4,82 kHz, which means its GBW > 1.01 MHz..

To obtain less than 10% error on the 4.82 kHz frequency, the op amp gain should be at least 20 dB above $1/\beta_{V2(res)}$. that is GBW > 530.2 kHz.

**The worst case minimum GBW is therefore 1.01 MHz.**